Lateral Mixing DRI Analysis: Submesoscale, Fine- and Microstructure Surveys of Internal Waves, Turbulence and Water-Mass Variability

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LONGTERM GOALS

My main interests is in smallscale ocean physics processes as they contribute to stirring and mixing in order to understand and parameterize their impact on larger scales. This includes phenomena ranging from the microscale (1 cm) up to the mesoscale (10-100 km) including near-inertial and tidal internal waves, vortical mode, fronts, turbulence production and salt fingers.

OBJECTIVES

To better understanding of isopycnal stirring and mixing on horizontal lengthscales between 0.1-10 km (meso- submesoscale) as part of the Lateral Mixing DRI.

APPROACH

My contribution to the 3-ship Lateral Mixing DRI June 2011 field program in the Sargasso Sea was to towyo a Rockland Scientific horizontal fine- and microstructure profiler (Hammerhead) to characterize the internal wave and turbulence fields in dye streaks and water-mass anomalies. This platform carries finescale Sea-Bird sensors for temperature, conductivity and pressure as well as Chelsea and WetLab optical sensors for chlorophyll, fluorescence and backscatter. A microthermistor rake on the nose measured temperature microstructure. Nine 5-9 h towyos were carried out over the course of the cruise, spanning lateral scales of 1 cm to O(10 km) at two sites: a low-energy ‘big nothing’ site with little or no eddy field and a region of weak O(0.1*f*) confluence. These 2-km radius towyos followed dye streak injections and were centered within ± 5 m of the dye-injection target σ_θ. They were embedded in larger-scale towyo surveys by Craig Lee, Jody Klymak and Murray Levine. They were centered on Lou Goodman’s Gateway buoy and enclosed box surveys by Lou Goodman’s T-REMUS.

WORK COMPLETED

Data collection was successful with both natural (water-mass aka spice) and anthropogenic (dye) finestructure detected on scales of O(100-1000 m). Preliminary results describing this finestructure in

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the spatial and spectral domains have been presented at the LatMix Portland and Woods Hole analysis meetings, and the 2011 Ocean Sciences conference in Salt Lake City.

RESULTS

Of the LatMix towyo assets, Hammerhead has the potential of resolving the smallest lateral scales along isopycnals (better than 100 m) so analysis has focused on spatial and spectral analysis to characterize spice and dye finestructure. At both sites, density stratification was dominated by temperature. Water-mass anomalies S' associated with stirring along isopycnals were weak at quiet site 1. They were stronger at confluent site 2, taking the form of a water-mass discontinuity (Fig. 1) aligned along the confluent axis that sharpened and weakened over the course of the 13-19 June period of sampling. The width of this discontinuity L together with the confluence α provides a 'largescale' measure of the isopycnal diffusivity $K_h \sim \alpha L^2 < 1\text{-}2\ \mathrm{m}^2\ \mathrm{s}^{-1}$ on 100-1000 m scales based on the site-2 confluence dropping from $0.2f$ to $0.1f$ after a day and a half and discontinuity widths $L < 300$ m. Water-mass variability was vertically coherent over the 10-m vertical aperture window (Fig. 2). Isopycnal displacements ξ were 2-4 m at both sites (Fig. 2), consistent with Lagrangian float estimates (D'Asaro). At quiet site 1, these were uncorrelated with salinity anomalies so likely due to internal waves. At confluent site 2, there was some S'- ξ correlation, suggesting that the water-mass front was a dynamical thermal-wind feature.

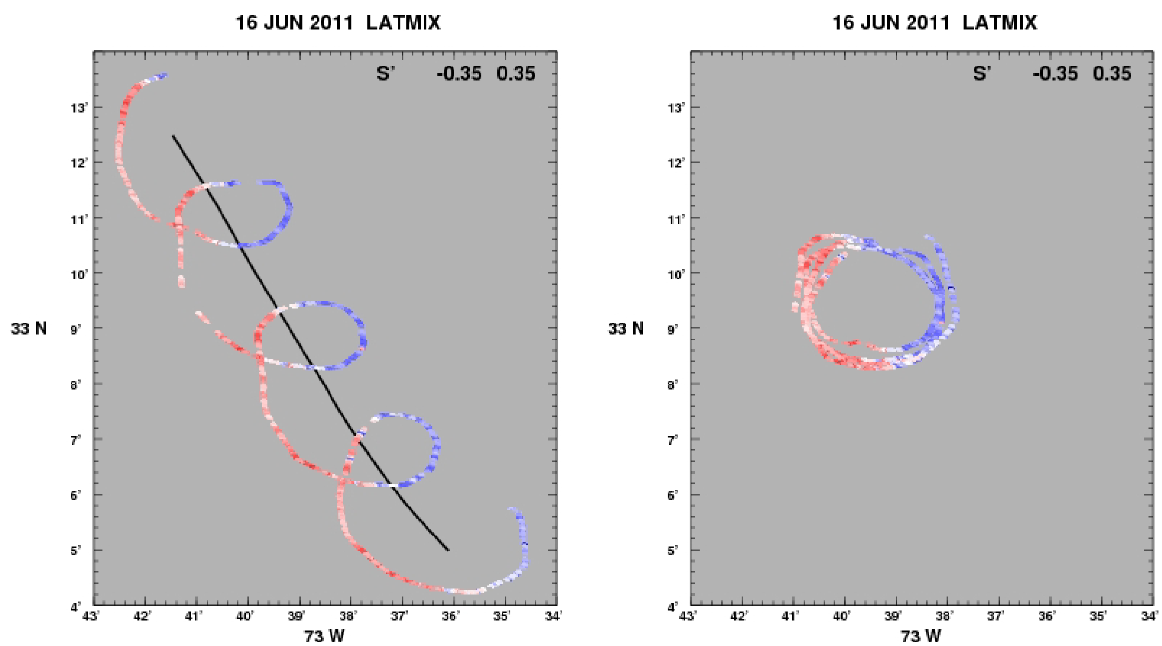

Figure 1: Salinity anomalies S' along the 16 June Hammerhead track at confluent site 2 in Eulerian coordinates (left) with Lou Goodman's Gateway buoy track overlaid (black line), and converted to Lagrangian coordinates using the Gateway buoy drift (right). Anomalies on all sampled density surfaces are overplotted. A sharp water-mass discontinuity runs NNW-SSE.

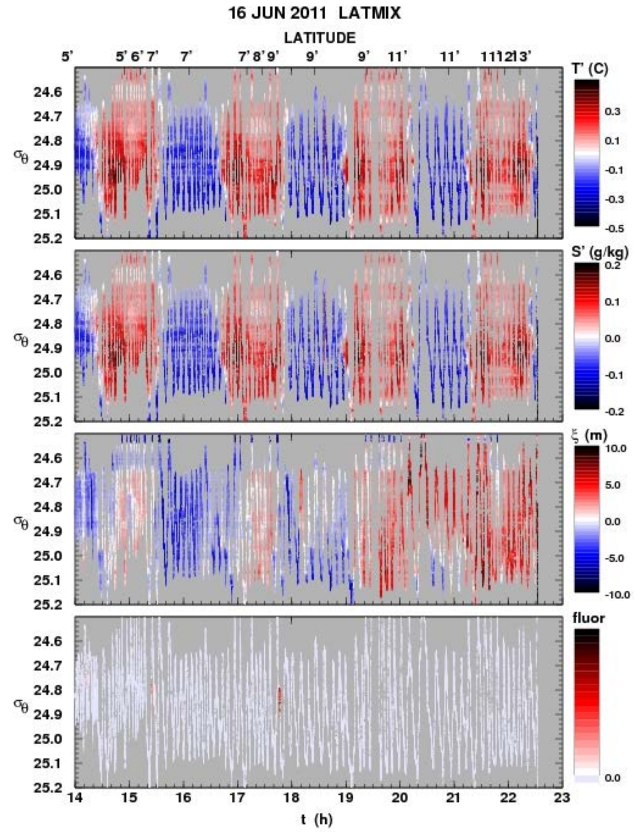

Figure 2: Temperature anomalies T', equivalent salinity anomalies S', isopycnal displacements ξ and fluorescence as a function of density σ_θ and time t (in UTC hours on 16 June) along the 16 June Hammerhead towyo track. Repeated crossings of the sharp water-mass discontinuity are evident in T' and S'. This discontinuity underwent sharpening and weakening over 14-19 June under the confluent flow. It is partially correlated with displacement ξ because it is also dynamic with a velocity jet signal. Fluorescein dye was occasionally but not always encountered coincident with the water-mass discontinuity.

Horizontal wavenumber spectra have been computed (Fig. 3 upper) for comparison with the theoretical spectra (Fig. 4). Hammerhead spectra span horizontal wavenumbers k_h = 0.1-10 cpkm (λ_h = 1-10 km) with an order-of-magnitude difference in spectral level at the 2 sites. Spectral slopes go as k_h^1. While this is consistent with expectations from QG stirring of a passive tracer, Hammerhead spectra differ dramatically from those Jody Klymak has computed from his MVP surveys at site 2 (Fig. 3 lower). The Hammerhead spectra have less variance at lower wavenumbers O(0.1 cpkm) and bluer slopes. Dr. Klymak and I are exploring possible explanations for these differences. The Hammerhead k_h^1 gradient spectra are consistent with a field of filaments while the observed structure (Fig. 1) is of an isolated front which should produce a k_h^0 spectra at low wavenumber, rolling off at higher wavenumbers because of the front's finite width. The spectra were computed differently. Isopycnal Hammerhead data was first binned into a structure function $S'_1S'_2$ vs. separation Δr then fit with Bessel functions $J_0(k_n\Delta r)$ including all isopycnals (D'Asaro and Perkins 1984; Kunze and Sanford 1991) which are the appropriate fitting functions for irregular sampling of a horizontal field. However, contamination could occur either from (i) failing to correctly advect the field into a horizontally Lagrangian coordinate system (Fig. 1) or (ii) unfiltered spikes introduced by incorrect transformation onto isopycnal coordinates. MVP data were collected on a more regular rectilinear grid and have been

interpolated onto a regular grid, then Fourier-transformed. The highest wavenumbers (Fig. 3 lower) have not been corrected for interpolation but this is unlikely to steepen the slope to +1.

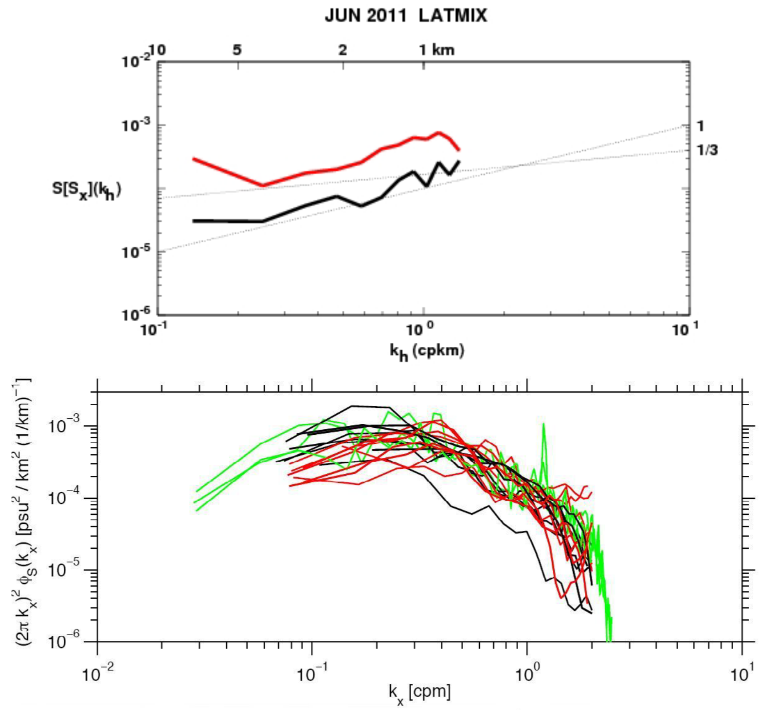

Figure 3: Horizontal wavenumber spectra of isopycnal salinity gradients from Hammerhead (upper panel) and the UVic MVP (lower panel, Klymak). In the upper panel, the black spectrum is from the quiet site 1 and the red spectrum from the confluent site 2. The lower panel includes only spectra from site 2. Compared to the MVP spectra, the Hammerhead spectra exhibit an order-of-magnitude deficit for k_h O(0.1 cpkm) which appears to be due Hammerhead measurements being in a region of weaker overall variability. Hammerhead spectra also exhibit a +1 slope while the MVP spectra are red for k_h > 0.2 cpkm.

Another possibility is that the 2 data sets simply sampled different parts of a heterogeneous field; while the Hammerhead site 2 survey only covered a ~5-km diameter region, MVP ranged over a broader area that appears to have included more water-mass variability.

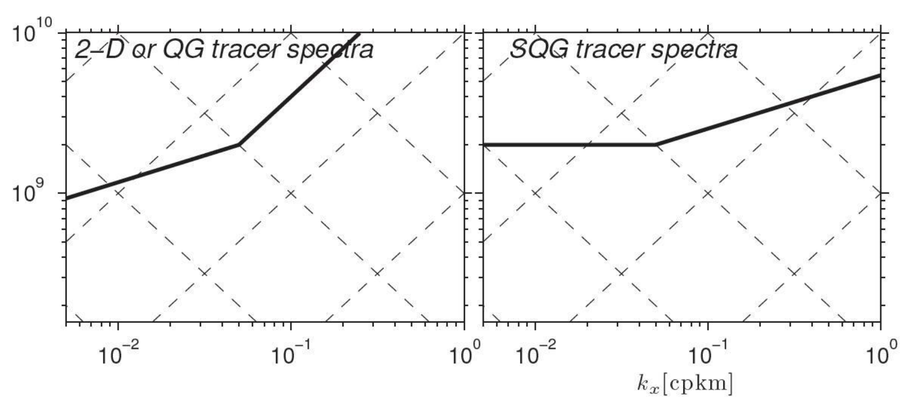

Figure 4: Theoretical tracer spectra for a quasigeostrophic (left) and surface quasigeostrohic (right) eddy field.

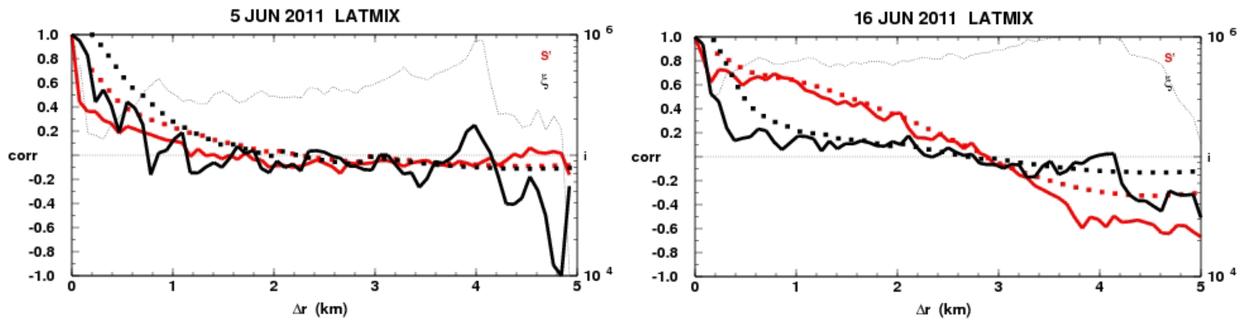

Figure 5: Structure functions of salinity anomaly S' and isopycnal displacement ξ as a function of along-isopycnal lateral separation Δr at the quiet site 1 (left) and confluent site 2 (right). Salinity anomalies exhibit longer integral lengthscales at the confluent site.

IMPACT/APPLICATION

While the Hammerhead horizontal wavenumber spectra for along-isopycnal spice gradient is consistent with QG tracer predictions, they don't agree with MVP spectra. The reasons for this discrepancy are under investigation but we have reason to believe that the +1 slope from Hammerhead (Fig. 3 upper) is not correct. If this is the case, the next question is why the QG and SQG spectra predict steeper blue spectra than observed. While one might argue that Hammerhead sampled too small a region, MVP covered much more territory so inadequate sampling of a statistically heterogeneous field seems an unlikely explanation.

RELATED PROJECTS

Participation in the LatMix data collection was supported by previous ONR grant "The Role of Biologically-Generated Turbulence in the Upper Ocean" (with John Dower and Richard Dewey, UVic) N0000140810700, which supported Masters student Shani Rousseau and PhD. student Mei Sato to better understand the role of swimming marine organisms in the production of turbulent mixing. Rousseau's research was based on a dozen dawn and dusk microstructure profile time-series in Saanich Inlet as well as a dozen dawn and dusk time-series collected in the open ocean. It concluded that, while there appeared to be weak enhancement of the turbulent dissipation rate during diel vertical migration of krill aggregations, it was insufficient to be of global significance (Rousseau *et al*. 2010). Sato is more broadly examining diel migration patterns. She has used a continuous 2-year time-series of upward-looking echosounder data from the VENUS observatory to quantify and explain temporal variability of the diel migrating krill layer in a coastal inlet, finding seasonal lags relative to civil twilight that appear to be due to changes in the krill life cycle (Sato *et al.* submitted). In a second project, she is analyzing a one-month time-series of turbulence in the inlet to characterize the variability and its causes. The PI also used this support to address the notion that microscopic swimming marine organisms could induce mixing by dragging fluid in their wake even at low Reynolds number, pointing out that papers on this subject (e.g., Katija and Dabiri 2009; Dabiri 2010; Thiffeault and Childress 2010) had neglected the role of molecular diffusion which will act to shortcircuit property transport (Kunze 2011).

In preparation for the LatMix experiment, Drs. Jody Klymak (UVic), Patrick Cummins (IOS BC) and the PI conducted a pilot dye study in Saanich Inlet during May 2009. I injected two streaks of dye on different density surfaces, nominally at 82- and 120-m depth. These were tracked over a week using 2 ships and the 2 towyo bodies. This work provided a test of our ability to find and survey dye streaks using a new towyo winch and a new log-scale Chelsea fluorescein sensor over an extended period. The dye streaks injected in the north end of Saanich Inlet were carried southward in a western boundary current, then northward along the eastern boundary in a hitherto unknown cyclonic circulation likely related to tidal rectification over sloping topography. We also observed more horizontal stirring of the streaks than anticipated, likely due to tidal headland eddies.

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PUBLICATIONS

N/A